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EXPLORATORY FLIGHT INVESTIGATION OF AIRCRAFT RESPONSE TO THE WING VORTEX WAKE GENERATED BY THE AUGMENTOR WING JET STOL RESEARCH AIRCRAFT

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16. Abstract

A brief exploratory flight program was conducted at Ames Research Center to investigate the vortex wake hazard of a powered-lift STOL aircraft. The study was made by flying an instrumented Cessna 210 aircraft into the wake of the Augmentor Wing Jet STOL research aircraft at separation distances from 1 to 4 n.mi. Characteristics of the wake were evaluated in terms of the magnitude of the upset of the probing aircraft. Results indicated that within 1 n.mi. separation the wake could cause rolling moments in excess of roll control power and yawing moments equivalent to rudder control power of the probe aircraft. Subjective evaluations by the pilots of the Cessna 210 aircraft, supported by response measurements, indicated that the upset caused by the wake of the STOL aircraft was comparable to that of a DC-9 in the landing configuration.

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NOTATION

a_x, a_y, a_n	inertial acceleration along the longitudinal, lateral and vertical axes
b	aircraft wing span
C_ℓ	rolling moment coefficient
$C_{\ell vortex}$	vortex induced rolling moment coefficient
$C_{L_{max}}$	maximum lift coefficient
C_{ℓ_β}	$\partial C_\ell / \partial \beta$
C_n	yawing moment coefficient
g	acceleration due to gravity
I_{xx}, I_{yy}, I_{zz}	body axis moments of inertia
p,q,r	inertial body rates about longitudinal, lateral and vertical axes
q	dynamic pressure (eqs. 1, 2 and 3)
S	aircraft wing area
V	flight velocity
$(\cdot)$	derivative with respect to time
β	angle of sideslip
δ_a	aileron deflection
δ_r	rudder deflection
δ_θ	longitudinal control deflection
δ_ϕ	lateral control deflection
δ_ψ	rudder pedal deflection
ν	Pegasus nozzle deflection (AWJSRA)

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INTRODUCTION

STOL aircraft could be used for short-haul transportation to increase the capacity and convenience of our domestic transportation system. These aircraft would operate from existing interurban airfields and provide transportation both to other interurban locations and to major airports serving urban areas.

The capacity of the interurban airfields to handle the increased traffic imposed by a STOL network may be adversely affected by STOL wake vortex characteristics. Even though STOL aircraft are smaller and lighter than current jet transports, it is possible that their wake will create an equivalent hazard due to the high lift and low speed typical of STOL terminal area operation. Furthermore, use of interurban airfields implies an operational mix of the STOL aircraft with general aviation aircraft, and the latter have been shown to require large separations from current jet transports to eliminate the hazard from wake vortices (see refs. 1 through 3).

As noted above, on the basis of speed and lift alone, the wake vortices from a STOL aircraft would be expected to be as hazardous as those from much heavier conventional aircraft. However, other factors such as the use of very high lift flap systems, and powered-lift might alter the vortex characteristics markedly. To investigate this possibility a brief flight investigation of the wake vortex characteristics of a specific powered-lift STOL aircraft was conducted. This report presents the results of this investigation and compares the hazard with that generated by conventional aircraft. The results were obtained in a single flight in which the response of a Cessna 210 flying in the wake of the Augmentor Wing Jet STOL Research Aircraft (AWJSRA) was measured. The Cessna 210 was chosen as the probe aircraft to permit comparisons with an earlier study in which this aircraft probed the wakes of conventional jet transports (ref. 1).

TEST AIRCRAFT

The general arrangement of the two aircraft used in the wake vortex study is shown on figures 1 and 2. Further details of the AWJSRA aircraft may be found in reference 4. For this flight test, the wake of the AWJSRA aircraft was marked by ejecting finely ground diatomaceous earth from each of its wing tips. The probe aircraft, a Cessna 210, was instrumented to measure linear

accelerations near its center of gravity, angular rates about three axes and angles of pitch and roll, control wheel and rudder pedal deflections, airspeed and altitude. The accuracies of these recorded parameters were within tolerances normally accepted in a stability and control or handling-qualities study.

TEST PROCEDURES

The altitude for the flights was maintained near 2750 m (9000 ft) in a stratum of low atmospheric turbulence. Each test series was initiated with the Cessna 210 positioned about 5 n.mi. behind the AWJSRA. The Cessna 210 would then close on the AWJSRA and encounter the wake at progressively smaller separation distances. The diatomaceous earth for marking the wake vortices was released in 10-sec bursts. The separation for each encounter was estimated from the elapsed time until the probing aircraft reached the segment of the wake marked by a particular burst. The flight conditions and the configurations of the AWJSRA for which data were obtained are listed in table 1.

DISCUSSION OF RESULTS

In the following sections the responses of the Cessna 210 to the AWJSRA wake are presented in terms of maximum recorded wake-induced rolling and yawing moments as compared with the Cessna 210 aileron and rudder control power. Upset dynamics resulting from the vortex encounters are summarized in terms of maximum measured excursions and accelerations at various spacings between the aircraft.

AIRPLANE RESPONSE TO VORTICES

A time history of a response of the Cessna 210 during a vortex encounter is shown in figure 3. These results illustrate the nature of a severe encounter and the techniques used to deduce roll rate and acceleration from the flight records.

The particular record shown was obtained at a separation distance of 1 n.mi. with the AWJSRA in the takeoff configuration. In this instance, the pilot attempted to hold the lateral controls fixed. The aircraft initially encountered the vortex at approximately 3.8 sec. This was followed 2 sec later by an encounter of somewhat greater severity that returned the aircraft to wings-level flight with a nose-down, yawed attitude.

The motion caused by the vortex was sufficient to exceed the limits of the instrumentation. The missing roll rate records were approximated by taking the slope of the roll angle trace as illustrated in figure 3a.

VORTEX INDUCED MOMENT

Net moments, expressed in coefficient form, were calculated from the Cessna 210 response data by the method detailed in reference 2; namely, subtracting airplane static, dynamic, and control moments from the measured angular acceleration. The following expressions were used for the computatons

$$C_{\ell_{vortex}} = \left[\frac{I_{xx}\,\dot{p}}{qsb} - C_{\ell_\beta}\beta + C_{\ell_{\delta_a}}\delta_a + C_{\ell_{\delta_r}}\delta_r + \frac{b}{2V}\left(C_{\ell_p}\,p + C_{\ell_r}\,r\right) \right] \tag{1}$$

$$C_{n_{vortex}} = \left[\frac{I_{zz}\,\dot{r}}{qsb} - C_{n_\beta}\beta + C_{n_{\delta_a}}\delta_a + C_{n_{\delta_r}}\delta_r + \frac{b}{2V}\left(C_{n_p}\,p + C_{n_r}\,r\right) \right] \tag{2}$$

table 2 lists inertias and aerodynamic derivatives used for the computations.

Air-flow direction sensors were not installed on the probe aircraft for direct measurement of sideslip angle. An estimate of sideslip angle was obtained by integrating change in yaw rate and lateral accelerations over a short time span immediately preceding the buildup in roll acceleration, as follows:

$$\beta = \tan^{-1}\left[\frac{q}{V}\int_{t_o}^{o} a_y\,dt - \int_{t_o}^{t} r\,dt \right] \tag{3}$$

The integration extended from a steady flight point before the vortex encounter, t_o, to the point of maximum roll acceleration, t.

Net vortex-induced moments in roll and yaw derived from the flight data are summarized in figure 4 as a ratio of the vortex-induced moment to the maximum control power of the encountering aircraft. The data are plotted against both separation between the aircraft and vortex age. The severity of the encounter at any separation distance will depend upon the trajectory of the penetrating aircraft relative to the vortex core. The envelope of the data points representing the maximum moments encountered is therefore of primary interest.

The flight data are compared with the maximum rolling moment to be expected on the basis of an empirical expression from reference 2 which, in turn, was based on the best fit to data obtained under similar conditions for conventional transport aircraft. Comparison of the induced moments anticipated from the AWJSRA with the envelope of the data points indicates that the level of the maximum induced moment is roughly 70 percent of that which would have been anticipated at one nautical mile separation distance. Furthermore, the data indicated that the rate of decay is more rapid than for conventional aircraft. This conclusion is tentative, however, because of the limited number of encounters at the greater separation distances and because of the decreased likelihood that any given encounter was of maximum severity. This is a consequence of the increased difficulty of visually locating the vortex trail at greater separation, the "dust" trail being only faintly discernible at distances greater than 1 nautical mile. The rapid diffusion of the dust that was ejected

from the wing tips could be caused by two effects. First, it was observed that the material was not ingested into the core of the principal vortex shed from the wing but instead spread thinly over a large area. Second, the rapid diffusion of the wake-marking material could have been caused by vortex dissipation. In the latter instance, the data are more likely to represent the envelope of the maximum expected response.

The data points were too few and scattered to establish consistent differences due to augmentor flap or Pegasus nozzle setting. It may be noted, however, that the maximum moments were obtained with the AWJSRA in the takeoff and landing configurations.

Previous studies of the wake encounter problem have presented summaries of the flight experience in terms of maximum excursions measured by the probing aircraft. Shown on figures 5 and 6 are summaries of the Cessna 210 encounter experience in terms of maximum roll rate, $|p|_{max}$, and maximum change in roll angle, $|\Delta\phi|_{max}$. Also shown for comparison are upper bounds of these two parameters measured when the Cessna 210 was flown into wakes from the DC-9 and CV-990 aircraft, as reported in reference 1. In terms of $|p|_{max}$ and $|\Delta\phi|_{max}$ the data indicate that the Cessna 210 was upset by the wake of the AWJSRA at least as severely as by the DC-9 at comparable separation distances. When separation is expressed in terms of time, the severity of the encounter approaches that due to the wake of the CV-990.

The maximum responses in normal acceleration, resulting from the wake encounters, are summarized in figure 7 as a function of separation distance and vortex age. A ±1.0 g envelope about trim would generally describe the flight experience, with no definite trend noted toward a reduction in transient load factors with increasing separation.

PILOT EVALUATION

An assessment of the hazard associated with encountering a wake vortex produced by STOL aircraft is presented from the pilot's viewpoint for consideration with the measured responses of the probe aircraft. This information is particularly pertinent because the pilot was best able to evaluate each upset relative to how closely the airplane was centered in the wake. The following paraphrases the pilots' comments:

Within 1 mile behind ghe AWJSRA deliberate vortex penetration with the Cessna 210 produced large bank angles ($\phi > 45°$) and abrupt "g" changes even when recovery control was applied promptly. Penetrations beyond 2 miles were almost all easily controlled in bank but both g loads and excursions in yaw were still large. Encounters at 2 miles and beyond were less certain since the diatomaceous earth in the vortex had dissipated and there was no way of knowing that the central part of the vortex had been penetrated.

Observations of the AWJSRA vortex showed that it expanded rapidly from the wing tip when the flaps were down, possibly because of an interaction with the disturbed flow from the augmentor flap segments. When the visible vortex diameter was small in relation to the Cessna 210, the encounters produced large roll motions as well as g loads, but when the diameter was large and less well defined yawing motions appeared dominant.

The decay in vortex strength was apparent during the flight. Since the AWJSRA was flying at about 85 knots, a range of 1.5 n.mi. represented a 1-min separation and by 3 n.mi., or 2 min, control was easily maintained during chance encounters.

There were enough encounters during the flight to compare subjectively the response of the Cessna 210 in the vortex of the AWJSRA and the DC-9 which had been observed in a previous test. There was no significant difference within the limited scope of these experiences and the AWJSRA wake vortex has the same effect on a Cessna 210 as a DC-9 wake at the same time spacing, assuming the generating airplanes are in a flaps down configuration.

CONCLUDING REMARKS

Within separation distances of 1 n.mi., the moments imposed by the vortex wake of the Augmentor Wing Jet STOL Research Aircraft were significantly greater than the lateral control power and about equivalent to the rudder control power of the Cessna 210. At separations greater than 1 n.mi., it was difficult to find the wake because of dispersion of the diatomaceous earth used to mark it. Consequently, fewer assured encounters were obtained at those separations, and those that were obtained were greatly reduced in severity. It is therefore not certain whether this reduction was caused by dissipation of the wake or failure to penetrate the core.

An evaluation by the pilots of the Cessna 210 ranked the upset magnitude induced by the AWJSRA wake as comparable with that of a DC-9 aircraft in the landing configuration for comparable vortex age.

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1. Andrews, William H.; Robinson, Glenn H.; and Larson, Richard R.: Exploratory Flight Investigation of Airplane Response to the Wing Vortex Wake Generated by Jet Transport Aircraft. NASA TN-D6655, March 1972.

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3. Barber, Marvin R.; Kurkowski, Richard L.; Garodz, Leo; et al.: Flight Test Investigation of the Wake Turbulence Characteristics Behind a Medium Size Jet Transport During Two-Segment and Normal ILS Approaches. NASA TM-X62,398, January 1975.

4. Ashleman, R. H.; and Akavdahl, H.: The Development of an Augmentor Wing Jet STOL Research Airplane (Modified C-8A). NASA CR-114503, August 1972.

TABLE 1.– TEST CONDITIONS

	AWJSRA			Cessna 210			
Configuration	Airspeed (knots, IAS)	Flap deflection (deg)	Nozzle deflection (deg)	Airspeed (knots, IAS)	Flap detection (deg)	Nominal altitude (m (ft))	Nominal separation distance (n.mi.)
Cruise	130	5.6	6	110–130	0	2750(9000)	5,3,1
Take-off	85	30	6	75–100	10,20	2750(9000)	5,3,1
Landing	65	65	6	60–90	10,20	2750(9000)	5,3,1
Landing	65	65	70	80–95	10,20	2750(9000)	3,1

TABLE 2.– CESSNA 210 CHARACTERISTICS

INERTIAS

I_{xx} = 1780 kg-m^2 (1313 slug ft^2)

I_{yy} = 2650 kg-m^2 (1955 slug ft^2)

I_{zz} = 4430 kg-m^2 (3268 slug ft^2)

AERODYNAMIC DERIVATIVES

Derivative	Flaps up (deg)	10° Flap (deg)	20° Flap (deg)
C_{ℓ_β}	−0.00156	−0.00159	−0.00163
$C_{\ell_{\delta_a}}$	0.00163	0.00163	0.00163
$C_{\ell_{\delta_r}}$	0.00020	0.00020	0.00020
C_{ℓ_p}	−0.00855	−0.00855	−0.00855
C_{ℓ_r}	0.00341	0.00341	0.00341
C_{n_β}	0.00158	0.00149	0.00140
$C_{n_{\delta_a}}$	−0.000359	−0.000409	−0.000460
$C_{n_{\delta_r}}$	−0.00140	−0.00132	−0.00123
C_{n_p}	−0.00140	−0.00140	−0.00140
C_{n_r}	−0.00205	−0.00205	−0.00205
$C_{L_{max}}$	1.65	1.78	2.11

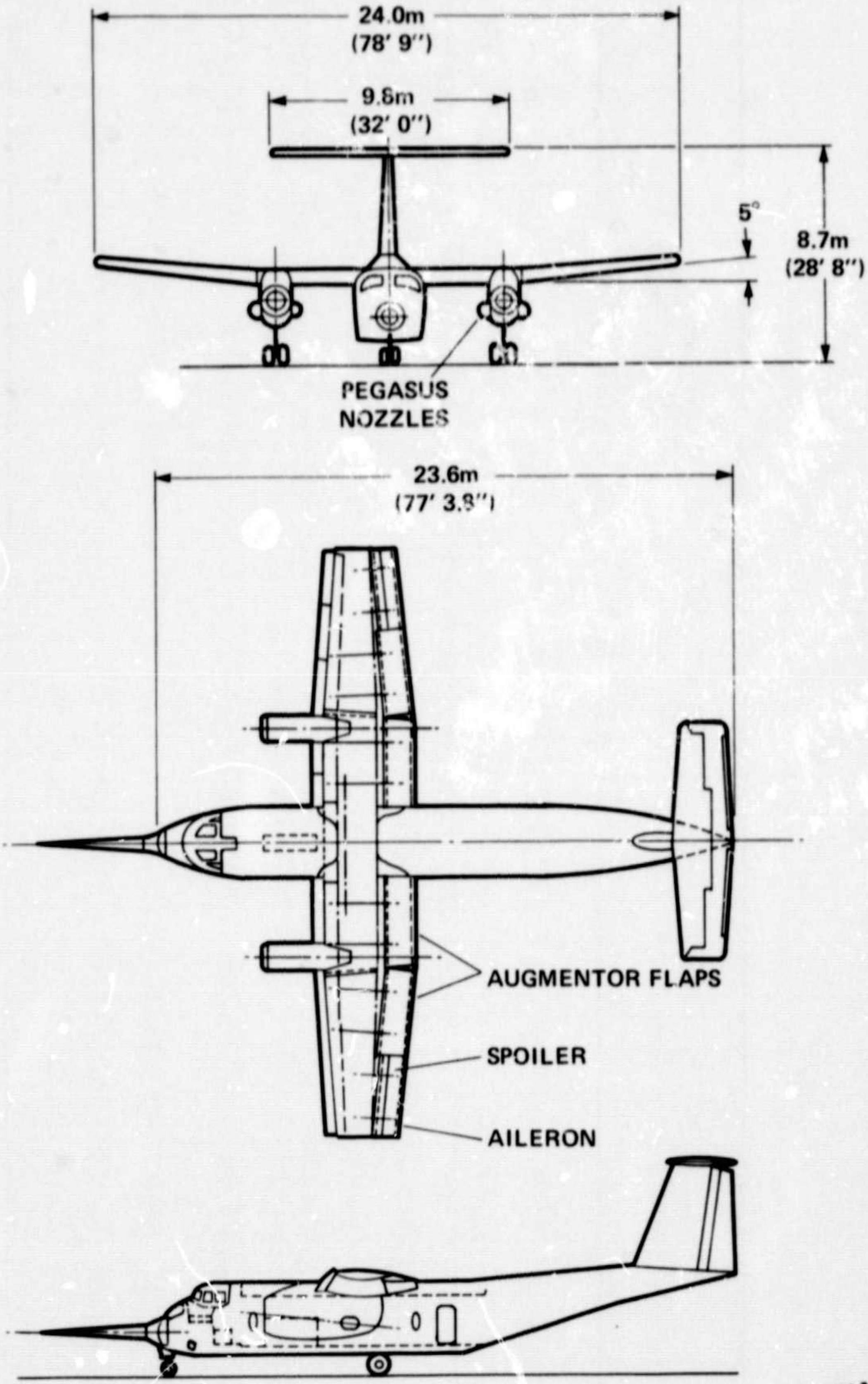


Figure 1.– Augmentor wing jet STOL research aircraft.

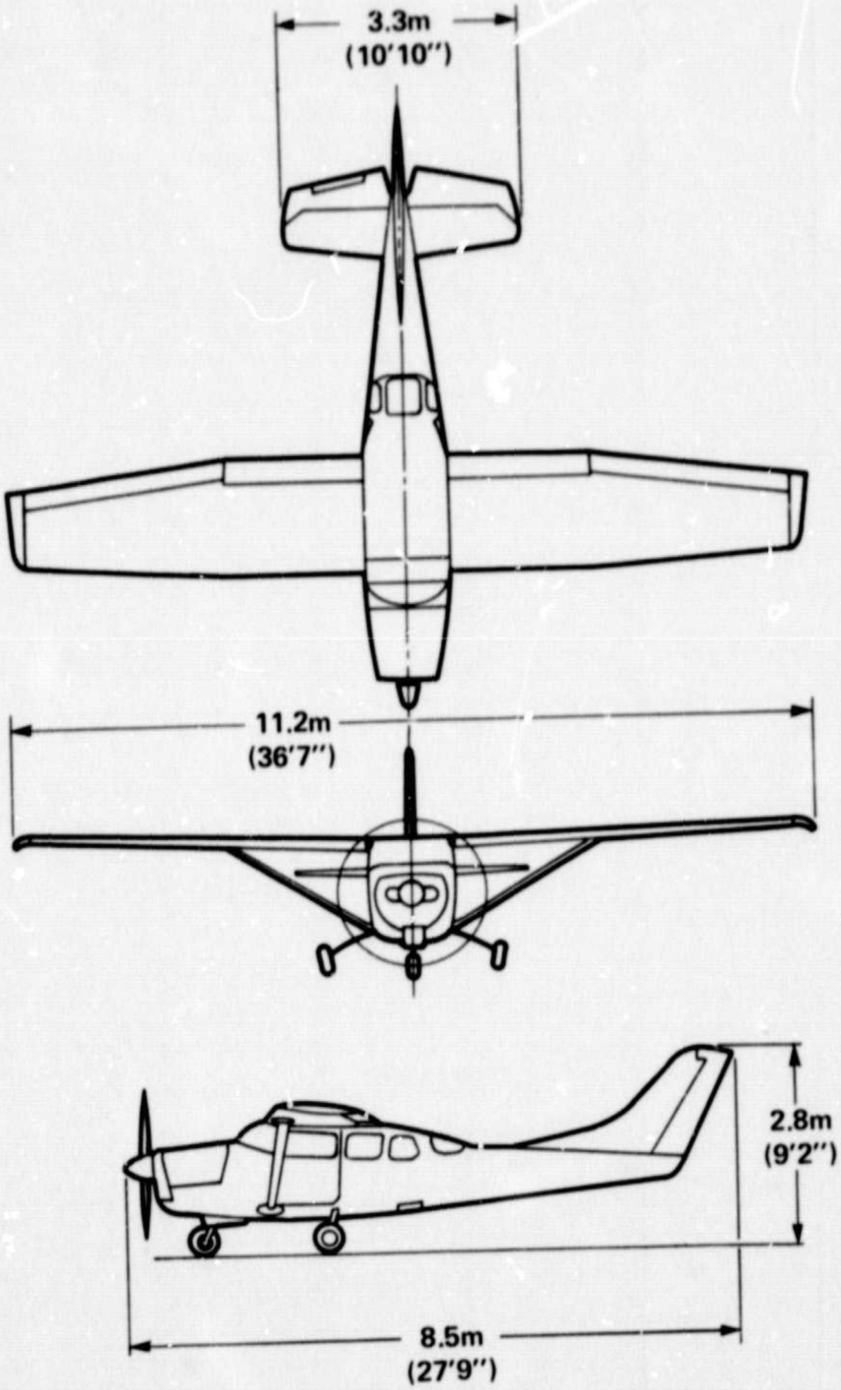
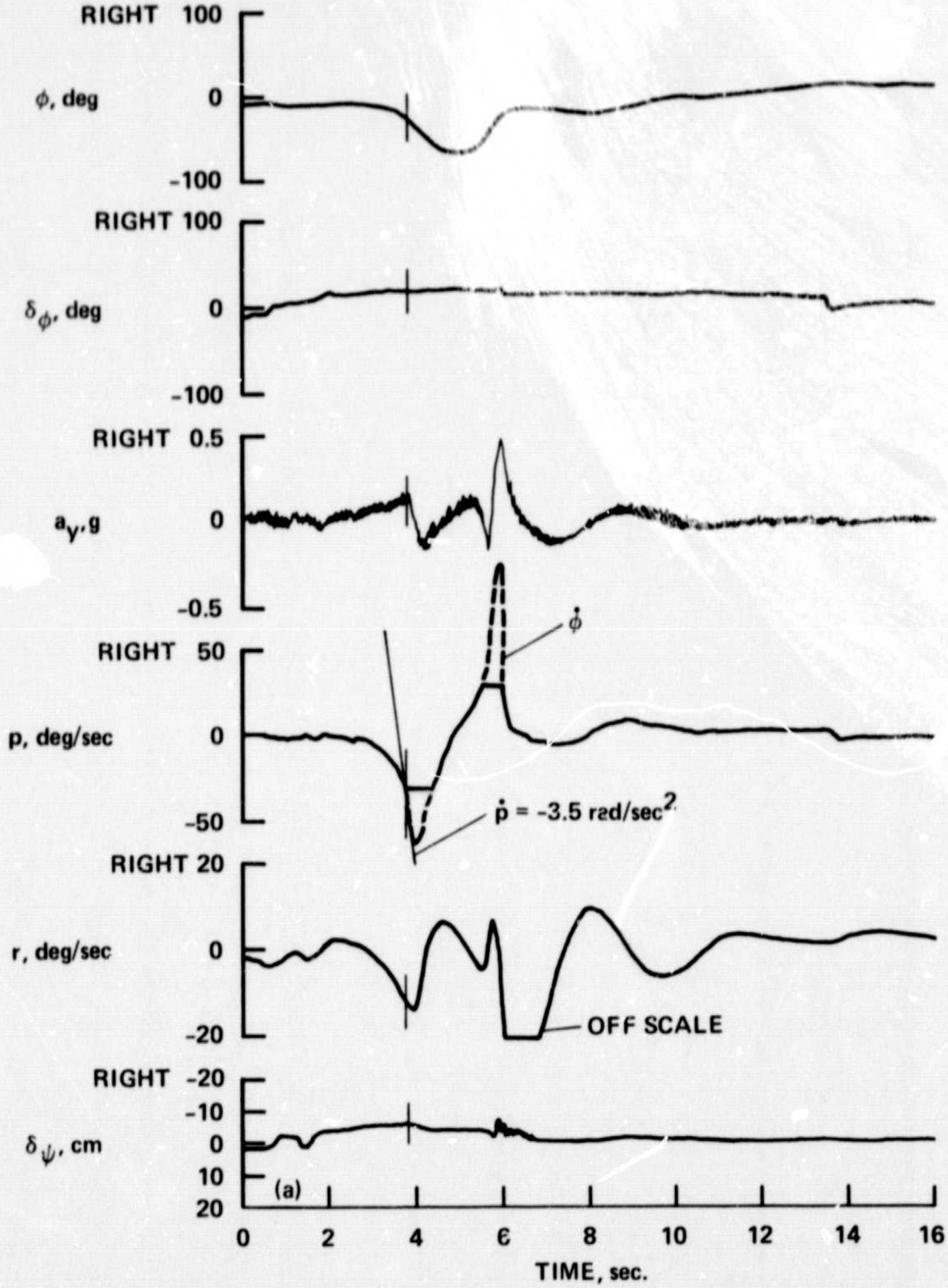
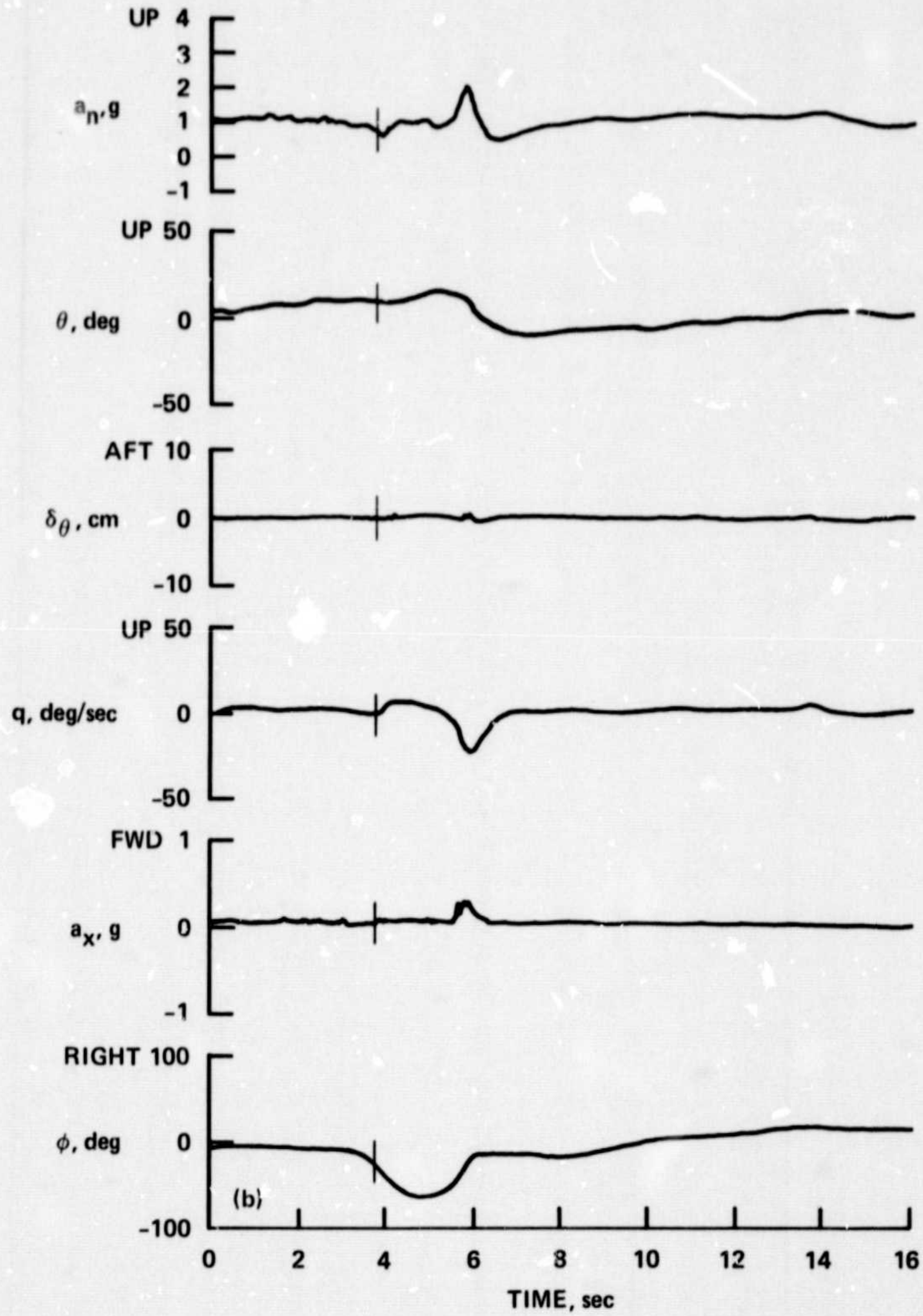


Figure 2.– Cessna 210 aircraft.



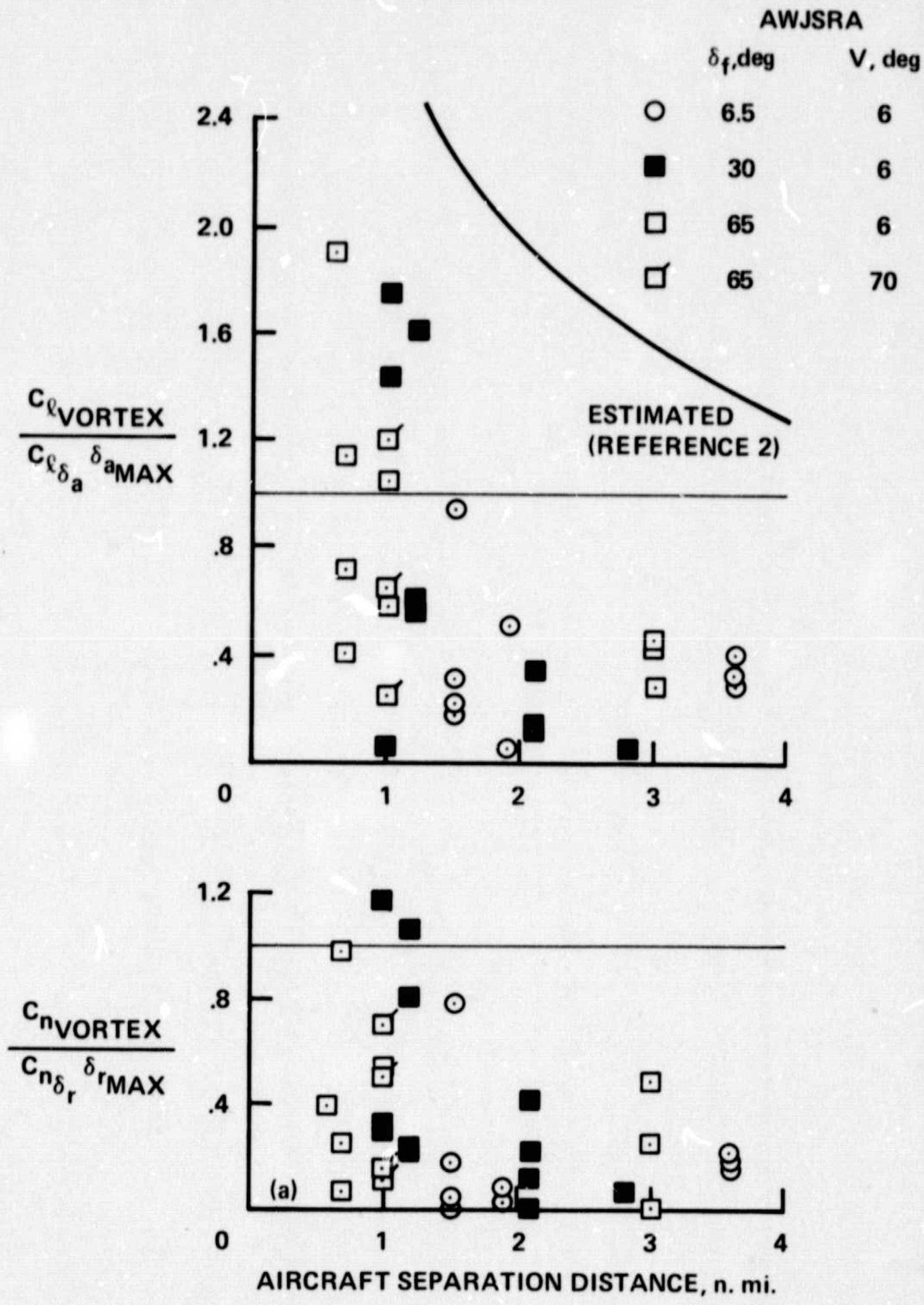
(a) Lateral-directional measurements.

Figure 3.– Time history of Cessna 210 response to the AWJSRA (takeoff configuration) wake. Separation distance 1 n.mi.



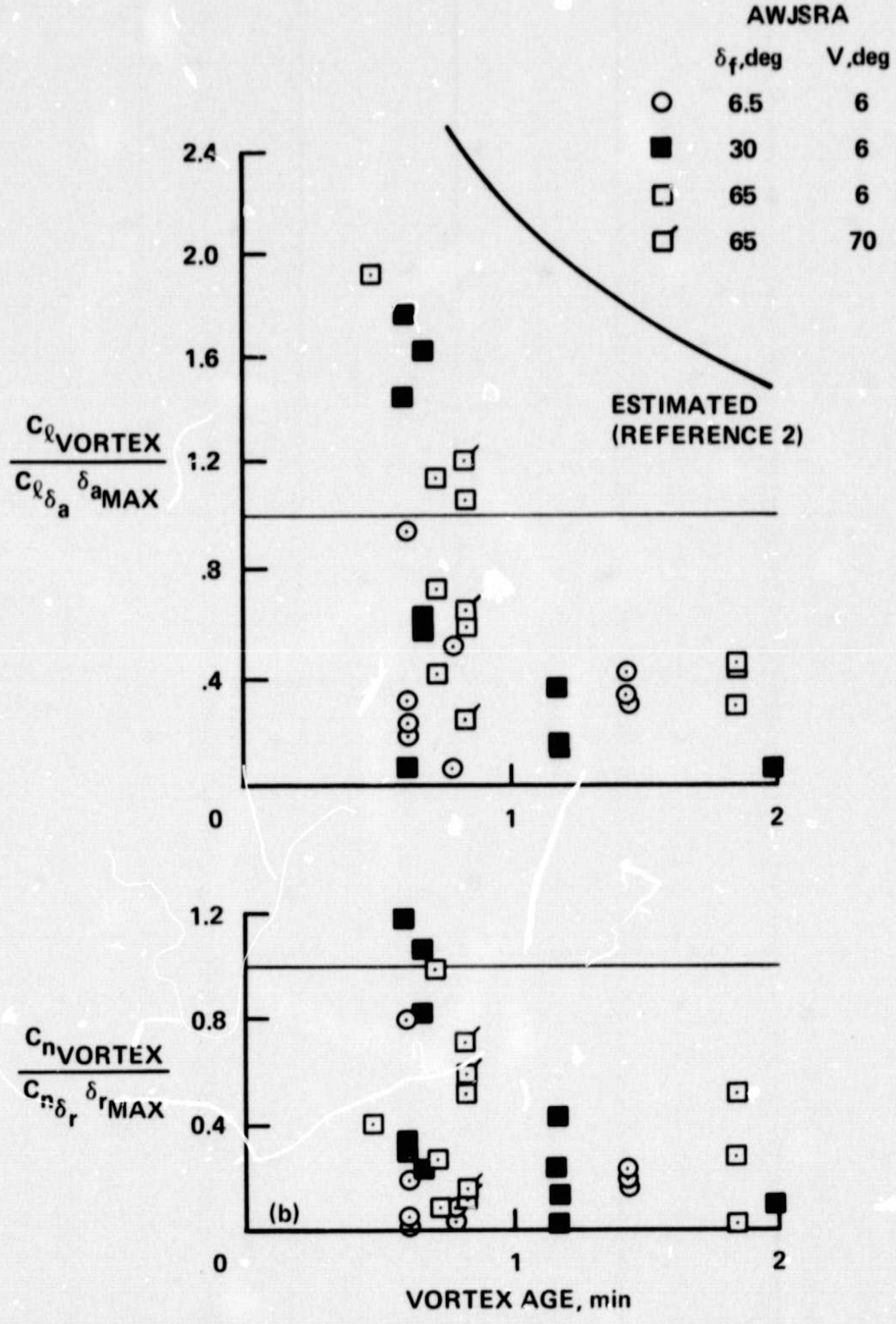
(b) Longitudinal measurements.

Figure 3.– Concluded.



(a) Comparison versus separation distance.

Figure 4.– Comparison of estimated and flight-test rolling and yawing moment ratios for the Cessna 210 in the wake of the AWJSRA.



(b) Comparison versus vortex age.

Figure 4.– Concluded.

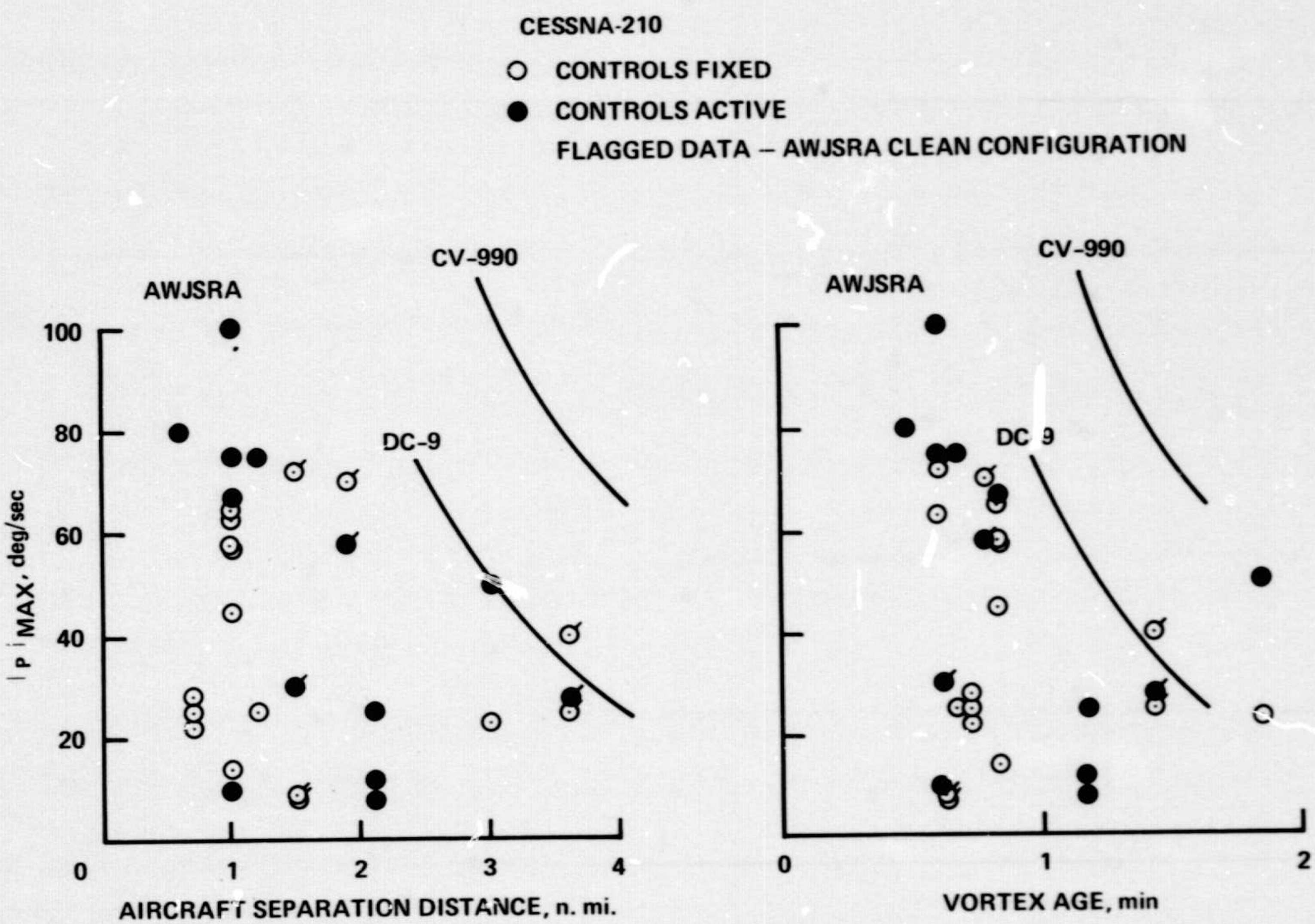


Figure 5.– Summary of Cessna 210 maximum roll rate following encounters with the wakes from three aircraft. (Flaps down configuration, except as noted.)

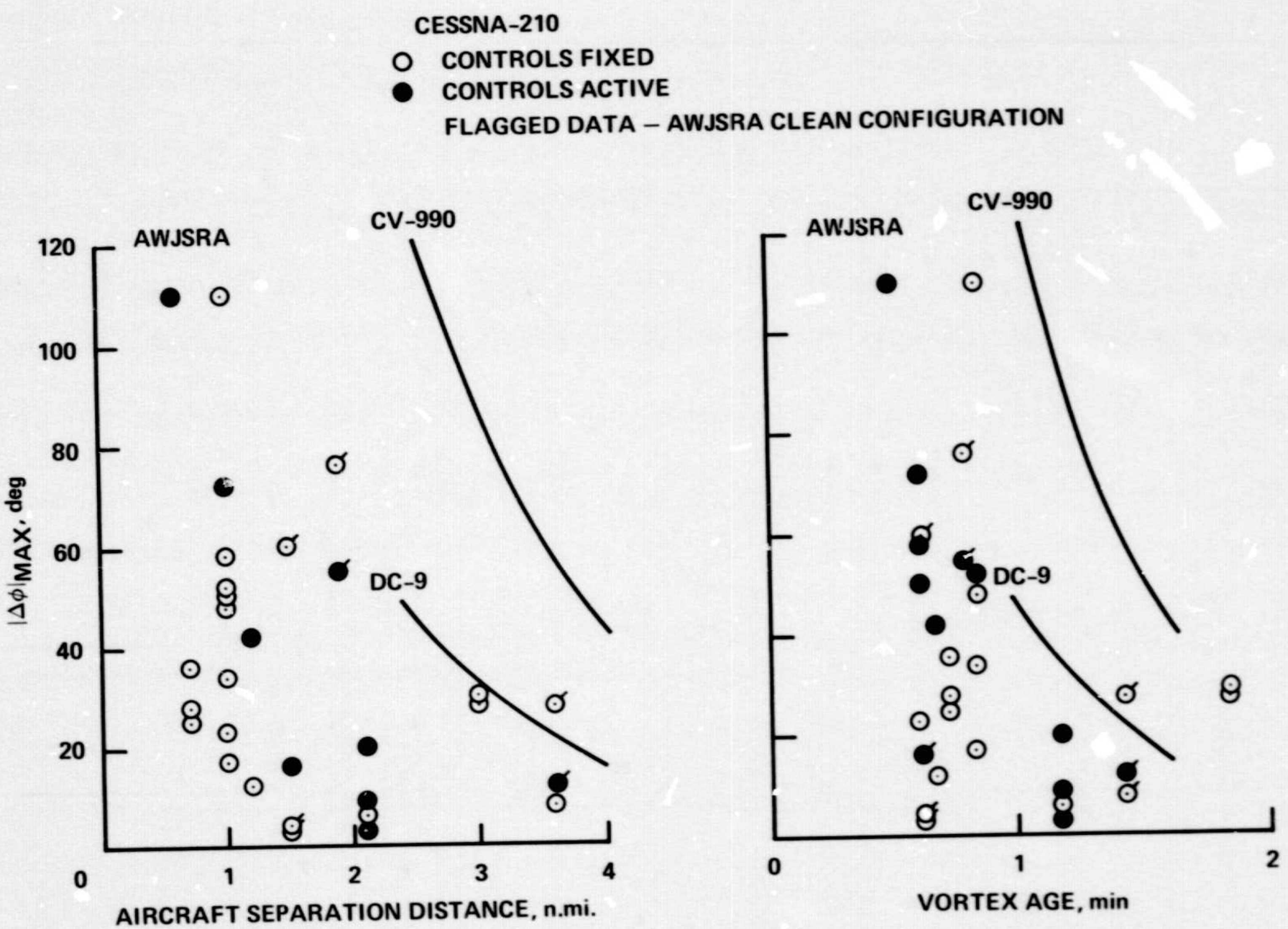


Figure 6.– Summary of Cessna 210 change in roll angle following encounter with wakes from three aircraft. (Flaps down configuration, except as noted.)

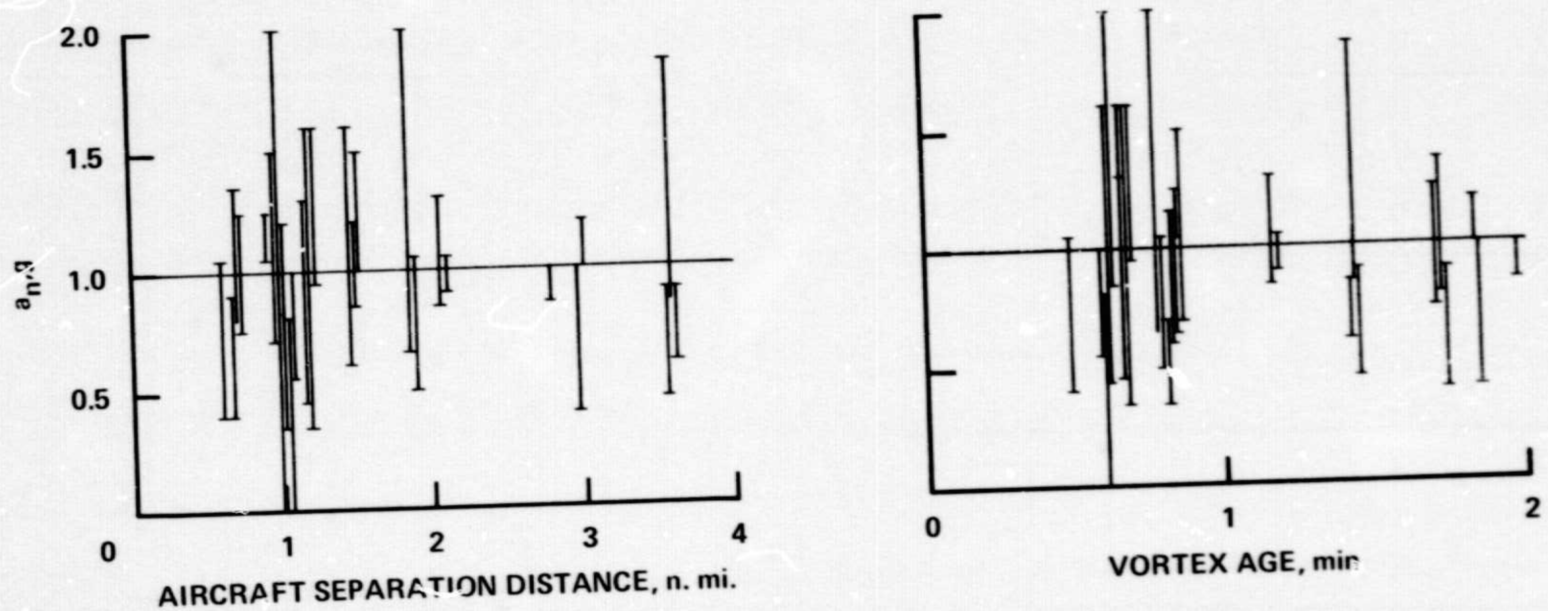


Figure 7.– Summary of Cessna 210 normal acceleration excursions following encounters with the AWJSRA Wake (all configurations).